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A STUDY ON FUEL ESTIMATION ALGORITHMS FOR A GEOSTATIONARY COMMUNICATION & BROADCASTING SATELLITE

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ABSTRACT

It has been developed to calculate fuel budget for a geostationary communication and broadcasting satellite. It is quite essential that the pre-launch fuel budget estimation must account for the deterministic transfer and drift orbit maneuver requirements. After on-station, the calculation of satellite lifetime should be based on the estimation of remaining fuel and assessment of actual performance. These estimations step from the proper algorithms to produce the prediction of satellite lifetime.
This paper concentrates on the fuel estimation method that was studied for calculation of the propellant budget by using the given algorithms. Applications of this method are discussed for a communication and broadcasting satellite.

Key words: orbit, satellite, communication

1. INTRODUCTION

The fuel estimation algorithms provide estimates of the hydrazine remaining in the on-board propellant tank. Two different methods of estimation are adopted. In the first, prediction of the fuel status at each stage of the mission is made using the rocket equations and a bookkeeping method. The second, i.e., PVT method (Trinks & Behring 1989) employs downlinked temperature and pressure telemetry from the spacecraft, and the ideal-gas law relations, to compute the current hydrazine mass.

The bookkeeping method includes detailed observation of a satellite operation and detailed record keeping during its mission lifetime to acquire its high accuracy for mission analysis purpose. However, the PVT method can be used at any point in the lifetime of mission without regard to mission history.

The main goal of this paper is to develop the fuel estimation algorithms, which can be used for the calculations of remaining fuel in a geostationary communication and broadcasting satellite.

Section 2 mainly deals with the relevant equations and appropriates explanations used to calculate the various geostationary communication satellite maneuvers and attitude control functions

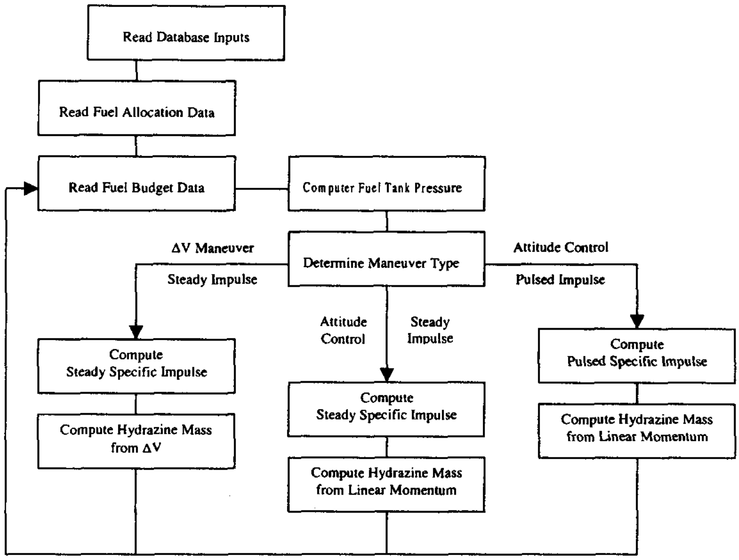

Figure 1. Fuel Budget Prediction Algorithm

(Eun & Suk 1996). The developed fuel estimation algorithms are also discussed. Applications to a geostationary three-axis communication and broadcasting satellite are given as examples in Section 3. Conclusions are dealt in the final section.

2. DETERMINATION OF ALGORITHMS FOR FUEL ESTIMATION

This section exemplifies how the following information can be used to determine the fuel remaining on-board the satellite during the whole mission lifetime. The spacecraft under consideration is assumed to be a geostationary communication satellite that shall be placed in orbit by Delta launcher system and an apogee kick motor. The spacecraft is also assumed to be three-axis stabilized except during the apogee kick motor burn, for which the spacecraft should be spun and de-spun. The propulsion system of the spacecraft is assumed to be a blowdown monopropellant hydrazine system.

2. 1 Theoretical Background

Throughout the lifetime of a spacecraft, various types of propulsive maneuvers will be performed to maintain the orbit and to control the attitude. By categorizing these anticipated burns, and accumulation of their total requirements, either in terms of ΔV or linear momentum, the fuel required to accomplish them can be computed. Aside from the rocket equation, which directly relates these quantities, some of the basic elements of ideal gas theory are employed to determine the pressure in the fuel tank, which dictates the specific impulse of the planned maneuvers. The followings detail the approach taken to predict the satellite fuel budget.

The maneuver sequence and its relevant functions are sequentially summarized in table 1 (Eun & Suk 1996).

Table 1. Maneuver Sequences and it's Relevant Functions for a Communication & Broadcasting Satellite.

Phase	Main Characteristics	Relevant Equation
De-spin	This is based on the laws of gyroscopic stability and conservation of angular momentum.	$DS_m = (SR_i - SR_f) \times (\frac{If}{rf}) \times (\frac{1}{Isp})$
Pre-Cession	140-degree precession is necessary to achieve apogee injection attitude.	$PCS_m = (PRS_a \times \frac{\pi}{180}) \times (SR \times \frac{\pi}{30}) \times (\frac{If}{M_{arm} \times Isp \times eff})$
Spin-up	Spin-up phase is to provide gyroscopic stiffness required for apogee kick motor burn.	$SU_m = (SR_f - SR_i) \times (\frac{If}{rf}) \times (\frac{1}{Isp})$
Apogee kick motor fire	The apogee injection maneuver uses a solid rocket motor.	$AKM_m = SC_m \times [1 - \exp(-\Delta V/(Isp \times g \times eff))]$
SA	Station acquisition phase corrects the dispersions from the transfer orbit injection and from the apogee burns.	$SA_m = SC_m \times [1 - \exp(-\Delta V/(Isp \times g \times eff))]$
SSK	The spacecraft inclination using ETs to provide the ΔV is controlled. Roll/yaw error control is maintained by on-pulsing Arcjet thrusters.	$NSSK_m = SC_m \times [1 - \exp(-\Delta V/(Isp \times g \times eff))]$ $\Delta V = DV/(1 + \alpha - \varepsilon)$ $eff = (1 - DR) \times PLC$
NSSKAC	Fuel consumption of NSSK AC is estimated by the equation.	$NSSKAC_m = \Delta V \times [(\alpha - \varepsilon)/(1 + \alpha - \varepsilon)]$
EWSK	The spacecraft longitude is maintained by continuous firing of one pair of Arcjet thrusters. Roll and yaw error are controlled by on-pulsing Arcjet thrusters. Pitch error is controlled by firing Arcjet thrusters	$NWSK_m = SC_m \times [1 - \exp(-\Delta V/(Isp \times g \times eff))]$
EWSKAC	Fuel consumption for EWSK AC is estimated by the equation.	$EWSKAC_m = EWCE \times EWSK_m \times EW_Isp/Isp$
MA	Environmental disturbances in pitch cause a wheel momentum change.	$MA_m = \frac{MD}{(M_{arm} \times Isp)}$
SRP	Normal EWSK maneuver is accomplished by the equation.	$SRP_m = SC_m \times [1 - \exp(-\Delta V/(Isp \times g \times eff))]$
SRAC	Fuel consumption for SRAC is estimated by the equation.	$SRAC_m = EWCE \times SRP_m \times SRP_Isp/Isp$

2.2 Fuel Budget Prediction

Fuel Budget Prediction Algorithm

The algorithm adopted to predict the hydrazine in the on-board fuel tank at various stages of the mission is demonstrated in Figure 1. The appropriate logic branch depends on whether the ΔV is provided, as in orbit correction maneuvers, or the linear momentum is specified, as for attitude control. Furthermore, the operational mode of the thrusters, either steady or pulsed, dictates the computation of the specific impulse for a given maneuver type.

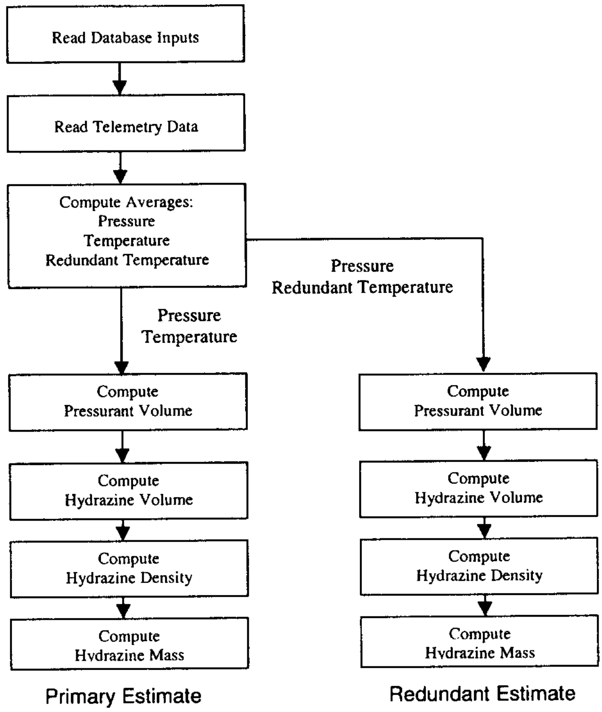

Figure 2. PVT Method Flowchart

Fuel Tank Pressure

The pressure in the fuel tank at any time can be computed from the nitrogen pressurant volume, using the ideal gas law;

$$P = P_0\left(\frac{V_{press_0}}{V_{press}}\right) \tag{1}$$

where, the pressure must be in absolute units. The subscript o refers to some epoch time at which both parameters are known, typically when the tank is loaded with fuel. The initial volume of the pressurant can be calculated from the equation of (2);

$$V_{press_0} = V_{\tan k} - \left(\frac{m_{hyd_0}}{\rho_{hyd}}\right) \tag{2}$$

where, m_{hyd} refers to the mass of hydrazine, V_{tank} is the total volume of the fuel tank, and ρ_{hyd} is the density of hydrazine. The latter two values are assumed to be constant. The current pressurant volume can then be obtained from the prior fuel used, Δm_{hyd}:

$$V_{press} = V_{press_0} + \left(\frac{\Delta m_{hyd}}{\rho_{hyd}}\right) \tag{3}$$

Combined with the loading pressure, P0, the results from equations (2) and (3) can be substituted into equation (1) to obtain the current pressure.

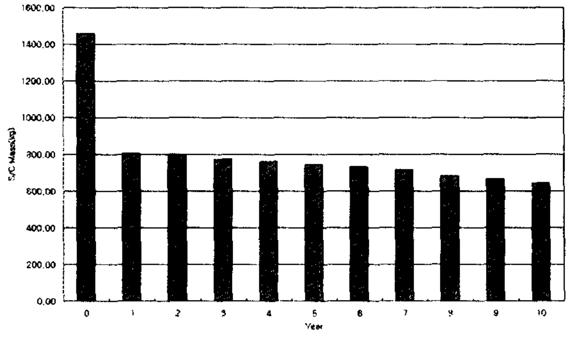

Figure 3. Variation of Spacecraft Mass with respect to its Mission Lifetime.

Specific Impulse

The specific impulse for a particular maneuver type depends on the fuel tank pressure, as well as the mode in which the transfer is operated.

Fuel Usage

The amount of fuel used in a particular maneuver depends on the magnitude of the impulse applied. Orbit acquisition and maintenance maneuvers are typically specified by the former, while attitude control burns are identified by the latter. When ΔV is given, the associated fuel use can be determined from the rocket equation;

$$\Delta m_{hyd} = m_{s/c}(1 - e^{-\Delta V/gI_{sp}}) \tag{4}$$

where, $m_{s/c}$ represents the current mass of the spacecraft prior to the maneuver.

2.3 PVT Estimation

The PVT method of the fuel budget accounting employs ideal gas laws to relate the pressure, volume, and temperature of the on-board hydrazine tank. Using telemetered data, this approach computes the volume of the nitrogen pressurant in the tank, and the corresponding volume and mass of the remaining fuel. This estimate serves as an independent verification of the value predicted by the bookkeeping method, which relies on fuel usage models. The followings discuss the algorithm developed to process the downlinked data, and to determine the amount of hydrazine in the fuel tank.

PVT Fuel Estimation Algorithm

The algorithm adopted to estimate the hydrazine remaining in the on-board fuel tank is charted in Figure 2. As indicated, two estimations of the mass are made based on the presence of redundant temperature measurements in the telemetry file.

Pressurant Volume

The volume of the nitrogen pressurant in the fuel tank at the time of the telemetry data can be computed from the ideal gas law.

$$V_{press} = \left(\frac{\overline{T}}{T_0}\right)\left(\frac{P_0}{\overline{P}}\right)V_{press0} \tag{5}$$

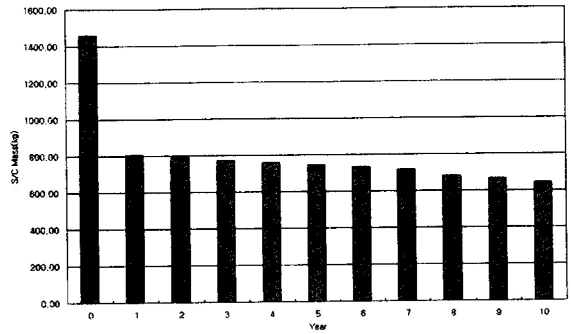

Figure 4. Estimations of Annual Hydrazine Use vs. Spacecraft Mission Lifetime.

where, both temperature (T) and pressure (P) must be in absolute units. The subscript o refers to some epoch time at which all three parameters are known, typically when the tank is loaded with fuel.

Hydrazine Volume

The volume of the fuel tank not occupied by the nitrogen pressurant contains hydrazine. Its volume at any time is simply the difference between the tank capacity and the pressurant volume.

$$V_{hyd} = V_{\tan k} - V_{press} \tag{6}$$

Hydrazine Mass

The mass of the hydrazine remaining in the fuel tank is the product of its volume and its density.

$$M_{hyd} = \rho V_{hyd} \tag{7}$$

3. COMPUTATION RESULTS

Before executing the fuel calculations software tool (Eun & Suk, 2000) which was developed by using the relevant algorithms represented in Section 2, several constraints should be proposed. The computation constraints are assumed to be given as follows;

- Spacecraft liftoff mass included apogee kick motor expendables = 1500 kg
- Apogee kick motor propellant loaded mass = 284 kg
- Apogee kick motor effective Isp = 289 sec.
- Lifetime of spacecraft = 10 years

By executing the fuel calculation software tool, several results are obtained as follows.

The variation of spacecraft mass with respect to its mission lifetime is shown in Figure 3. The nominal fuel remaining at the beginning of each year is obtained from the propellant budget analysis as shown in Figure 3. In Figure 3, propellant remaining between 0 and first year drops rapidly because of apogee kick motor fuel use.

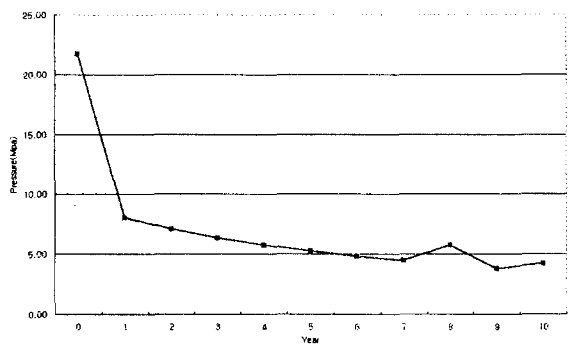

Figure 5. Variation of Estimated Pressurant with respect to Satellite Lifetime.

By solving the fuel budget calculations, the dry mass of the spacecraft turned out to be about 640 kg. Another important topic is pressure drop effect of blowdown propulsion system. From the beginning of the mission, helium gas pressure is affected by the amount of expelled propellant out of the tank. The estimated values of the annual hydrazine use are illustrated in Figure 4. This spacecraft model uses two different types of thrusters, which are arc-jet thrusters and ETs.

The variation of the estimated amount of pressurant consumption is depicted in Figure 5.

4. CONCLUSIONS

The basic idea behind fuel budgeting is an elementary one, centering primarily on proper bookkeeping of the hydrazine used during each maneuver. With accurate knowledge of the initial propellant load, the amount of fuel at any time is known based on what has been consumed. The errors in this approach stem from the inaccuracies associated with the estimation of hydrazine consumption.

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REFERENCES

Eun, J. W., & Suk, J. 1996, JA&SS, 13, 174

Eun, J. W., & Suk, J. 2000, Apparatus and Method for Estimating Remaining Fuel Quantity in geostationary earth orbit Communication Satellite Propulsion System, Apr. 25, 2000, U.S. Patent No.6, 055, 485

Trinks, H., & Behring, T. 1989, Proc. of 25th AIAA Joint Propulsion Conf., 1

LIST OF ABBREVIATION

AKM_m	Required propellant mass for apogee kick motor fire
DR	De-rating
DS_m	Required propellant mass for de-spin
DST	Dual-Spin Turn
DV	Fixed value given by mission analysis
eff	Efficiency
ET	Electrothermal thruster
E/W	East/West
EWCE	E/W-E/W coupling coefficient
EWSK	E/W stationkeeping
$EWSK_m$	Required propellant mass for E/W stationkeeping
EWSKAC	E/W stationkeeping attitude control
$EWSKAC_m$	Required propellantmass for E/W stationkeeping attitude control
$EW_I sp$	Specific impulse used for E/W stationkeeping
g	Gravitational acceleration
If	Spin inertia
Isp	Specific impulse
M_{arm}	Moment arm
MA	Momentum adjustment
MA_m	Required propellant mass for moment adjustment
MD	Average momentum disturbance per year
N/S	North/South
NSSK	N/S stationkeeping
$NSSK_m$	Required propellant mass for N/S stationkeeping
NSSKAC	N/S stationkeeping attitude control
$NSSKAC_m$	Required propellant mass of NSSKAC
PCS_m	Required propellant mass for precession
PLC	Geometric and plume loss contributor
PRS_a	Precession angle
PVT	Pressure/volume/temperature
rf	Moment arm of thrusters used for spin-up/down
SA	Station acquisition
SA_m	Required propellant mass for station acquisition
SC_m	Spacecraft mass
SPM	Spin precession maneuver
SR	Spin rate
SR_i	Initial spin rate
SR_f	Final spin rate
SRAC	Station repositioning attitude control
$SRAC_m$	Required propellant mass for station repositioning attitude control
SRP	Station repositioning
$SRP_I sp$	Specific impulse used for station repositioning
SRP_m	Required propellant mass for station repositioning
SU_m	Required propellant mass for spin-up
ΔV	Velocity change
α	Arc-jet thruster duty cycle
ε	ET thruster duty cycle
π	Pi